

**VERTICAL NANOTUBE SEMICONDUCTOR DEVICE STRUCTURES AND
METHODS OF FORMING THE SAME**

Field of the Invention

The invention relates to semiconductor device fabrication and, more particularly, to vertical semiconductor device structures, such as field effect transistors and capacitors, incorporating nanotubes as a device element and methods of
5 fabricating such vertical semiconductor device structures.

Background of the Invention

Traditional field effect transistors (FET's) are familiar conventional devices commonly incorporated as a fundamental building block into the intricate circuitry of integrated circuit (IC) chips. A single IC chip may feature many thousands to millions
10 of FET's, along with other passive components such as resistors and capacitors, interconnected by conductive paths. FET's operate by varying the resistivity of a channel in a channel region separating a source and a drain. Carriers flow from the source to the drain through the channel in proportion to the variation in electrical resistivity. Electrons are responsible for channel conduction in n-channel FET's and,
15 in p-channel FET's, holes are responsible for conduction in the channel. The output current of the FET is varied by application of a voltage to an electrostatically-coupled gate electrode located above the channel region between the source and drain. A thin gate dielectric insulates the gate electrode electrically from the channel region. A small change in gate voltage can cause a large variation in the current flowing from
20 the source to the drain.

FET's can be classified into horizontal architectures and vertical architectures. Horizontal FET's exhibit carrier flow from source to drain in a direction parallel to the horizontal plane of the substrate on which they are formed. Vertical FET's exhibit

carrier flow from source to drain in a direction vertical to the horizontal plane of the substrate on which they are formed. Because channel length for vertical FET's does not depend on the smallest feature size resolvable by lithographic equipment and methods, vertical FET's can be made with a shorter channel length than horizontal FET's. Consequently, vertical FET's can switch faster and possess a higher power handling capacity than horizontal FET's.

Carbon nanotubes are nanoscale high-aspect-ratio cylinders of carbon atoms proposed for use in forming hybrid devices. Carbon nanotubes efficiently conduct in their conducting form and act as a semiconductor in their semiconductor form.

Horizontal FET's have been fabricated using a single semiconducting carbon nanotube as a channel region and forming ohmic contacts at opposite ends of the carbon nanotube extending between a gold source electrode and a gold drain electrode situated on the surface of a substrate. A gate electrode is defined in the substrate underlying the carbon nanotube and generally between the source and drain electrodes. An oxidized exposed surface of the substrate defines a gate dielectric between the buried gate electrode and the carbon nanotube. Such horizontal FET's should switch reliably while consuming significantly less power than a comparable silicon-based device structure due to the small dimensions of the carbon nanotube. Horizontal FET's have been successfully formed under laboratory conditions by manipulating single carbon nanotubes using an atomic force microscope or coincidental placement of a single nanotube from a dispersed group of nanotubes. However, these methods of forming such horizontal FET device structures are incompatible with mass production techniques.

What is needed, therefore, is a vertical FET structure incorporating one or more semiconducting carbon nanotubes as a channel region that is compliant with mass production techniques.

Summary of the Invention

In accordance with the principles of the invention, a vertical semiconductor device structure includes a substrate defining a substantially horizontal plane, a gate electrode projecting vertically from the substrate, and at least one semiconducting

nanotube extending vertically through the gate electrode between opposite first and second ends. A gate dielectric, which may be disposed on the at least one semiconducting nanotube, electrically insulates the at least one semiconducting nanotube from the gate electrode. A source is electrically coupled with the first end of the at least one semiconducting nanotube and a drain is electrically coupled with the second end of the at least one semiconducting nanotube.

In another aspect of the invention, a method of forming a semiconductor device structure includes forming a conductive pad on a substrate and then growing at least one semiconducting nanotube extending substantially vertically from the conductive pad between a first end electrically coupled with the conductive pad and a second free end. The method further includes electrically insulating the at least one semiconducting nanotube with a gate dielectric and forming a gate electrode electrically insulated from and overlying the conductive pad, with the at least one semiconductor nanotube extending vertically through the gate electrode. A contact is formed that is electrically coupled with the second end of the at least one semiconducting nanotube and electrically insulated from the gate electrode.

Each semiconducting nanotube defines a channel region of a field effect transistor having a channel regulated by application of a control voltage to the gate electrode. Consistent with the principles of the invention, the length of the channel region between the source and drain is defined by the vertical dimension or thickness of the gate electrode without the limitations imposed by conventional lithographic processes used in semiconductor device fabrication to form channel regions in conventional field effect transistors.

In accordance with the principles of the invention, a semiconductor device structure includes a substrate defining a substantially horizontal plane, a conductive first plate disposed on the substrate, and at least one nanotube projecting vertically from the first plate. Each nanotube, which may have a conducting molecular structure or a semiconducting molecular structure, is electrically coupled with the first plate. Positioned vertically above the first plate and the nanotube is a conductive second plate electrically isolated from the first plate and the carbon nanotube by a dielectric layer.

In another aspect of the invention, a method of forming a semiconductor device structure includes forming a conductive first plate on a substrate and growing at least one nanotube extending substantially vertically from the first plate that is electrically coupled with the first plate. The method further includes encasing each
5 nanotube and covering the first plate with a dielectric layer, and forming a second plate overlying said first plate that is electrically isolated by the dielectric layer from each nanotube and the first plate.

Brief Description of the Drawings

The accompanying drawings, which are incorporated in and constitute a part of
10 this specification, illustrate embodiments of the invention and, together with a general description of the invention given above, and the detailed description of the embodiments given below, serve to explain the principles of the invention.

FIG. 1 is a cross-sectional view of a portion of a substrate with carbon nanotubes grown vertically on a patterned conductive catalyst pad;

15 FIG. 2 is a cross-sectional view similar to FIG. 1 at a subsequent fabrication stage;

FIG. 3 is a cross-sectional view similar to FIG. 2 at a subsequent fabrication stage;

20 FIG. 4 is a cross-sectional view similar to FIG. 3 at a subsequent fabrication stage;

FIG. 5 is a cross-sectional view similar to FIG. 4 at a subsequent fabrication stage;

FIG. 6 is a cross-sectional view similar to FIG. 5 at a subsequent fabrication stage;

25 FIG. 7 is a cross-sectional view similar to FIG. 6 at a subsequent fabrication stage;

FIG. 8 is a cross-sectional view similar to FIG. 7 at a subsequent fabrication stage;

30 FIG. 9 is a cross-sectional view similar to FIG. 2 at a subsequent fabrication stage in accordance with an alternative embodiment of the invention; and

FIG. 10 is a cross-sectional view similar to FIG. 9 at a subsequent fabrication stage.

Detailed Description of Specific Embodiments

The invention is directed to vertical field effect transistors (FET's) that utilize
5 carbon nanotubes as a semiconducting material for the channel region providing a
selective conduction path between a source and a drain when a voltage is applied to an
electrostatically-coupled gate electrode. In accordance with the principles of the
invention, the length of the channel region between the source and drain is defined by
the thickness of the gate electrode, which is substantially equal to the nanotube length,
10 and is not dependent upon a resolution-limited lithographic process. The carbon
nanotubes do not have to be individually manipulated for placement between a source
and a drain nor does device fabrication depend upon coincidental alignment with the
source and drain of one or more nanotubes randomly dispersed on the device surface.

With reference to FIG. 1, a catalyst pad 10 of a catalytic material suitable for
15 supporting the growth of carbon nanotubes 14 is formed as part of a pattern of many
pads 10 on a region of an insulating substrate 12. Carbon nanotubes 14 are oriented to
extend substantially vertically upward from the catalyst pad 10. The insulating
substrate 12 may be formed on a wafer (not shown) composed of any suitable
semiconductor material, including but not limited to silicon (Si) and gallium arsenide
20 (GaAs), upon which an insulating substrate 12, such as silicon oxide, may be formed.
The catalyst pad 10 may be formed by depositing a blanket layer of the catalytic
material on the insulating layer 12 by any conventional deposition technique
including, but not limited to, chemical vapor deposition (CVD) using suitable
precursors such as metal halides and metal carbonyls, sputtering, and physical vapor
25 deposition (PVD) and then employing a standard lithographic and subtractive etch
process to pattern the blanket layer. The catalytic material in catalyst pads 10 is any
material capable of nucleating and supporting the growth of carbon nanotubes 14
when exposed to appropriate reactants under chemical reaction conditions suitable to
promote nanotube growth. For example, suitable catalytic materials include, but are

not limited to, iron, platinum, nickel, cobalt, compounds of each of these metals, and alloys of each of these metals such as metal silicides.

Carbon nanotubes 14 are grown on the catalytic pad 10 by any suitable growth or deposition technique. In one embodiment of the invention, the carbon nanotubes
5 14 are grown by chemical vapor deposition (CVD) or plasma-enhanced CVD using any suitable gaseous or vaporized carbonaceous reactant including, but not limited to, carbon monoxide (CO), ethylene (C₂H₄), methane (CH₄), acetylene (C₂H₂), a mixture of acetylene and ammonia (NH₃), a mixture of acetylene and nitrogen (N₂), a mixture of acetylene and hydrogen (H₂), xylene (C₆H₄(CH₃)₂), and a mixture of xylene and
10 ferrocene (Fe(C₅H₅)₂) under growth conditions suitable for promoting carbon nanotube growth on the catalytic material forming the catalyst pad 10. The carbonaceous reactant and catalyst pad 10 may be heated to a temperature adequate to promote and/or hasten CVD growth. The reactant chemically reacts with the catalyst material of catalyst pad 10 to nucleate carbon nanotubes 14 and to sustain their growth
15 after nucleation. The catalyst material of the catalyst pad 10 participates in nanotube growth without itself being transformed or consumed by the chemical reaction transpiring at its exposed surface by reducing the activation energy for the reaction forming carbon nanotubes 14 to occur.

The carbon nanotubes 14 constitute hollow cylindrical tubes composed of
20 precisely arranged groups including hexagonal rings of bonded carbon atoms. The cylindrical tubes have a diameter ranging from about 0.5 nm to about 20 nm and a sidewall thickness of about 0.5 nm to about 3 nm. The carbon nanotubes 14 are expected to have a statistical distribution of heights or lengths each measured between a free end or leading tip 16 and a bonded end or base 18. The carbon nanotubes 14
25 extend on average substantially vertically upward from the catalyst pad 10 with a perpendicular or, at the least, approximately perpendicular orientation to the horizontal surface of the catalyst pad 10. The invention contemplates that one or all of the carbon nanotubes 14 may be inclined slightly from the vertical direction, as defined herein and that the nanotube orientation may be characterized by a statistical
30 distribution that, on average, is substantially vertical. The nanotube density and spacing between adjacent carbon nanotubes 14 will depend, among other variables,

upon the growth conditions. The carbon nanotubes 14 will typically grow at substantially random spatial locations on the exposed surface area of the catalyst pad 10.

Growth conditions of the CVD or plasma-enhanced CVD process are chosen for preferentially growing carbon nanotubes 14 having a semiconducting electronic structure or molecular structure. Alternatively, carbon nanotubes 14 having a semiconducting molecular structure may be preferentially selected from among a random collection of as-grown nanotubes 14 including both metallic and semiconducting molecular structures by, for example, applying a current sufficiently high to destroy nanotubes 14 having the metallic (e.g., conducting) molecular structure. Post-synthesis destruction of conducting carbon nanotubes is described in commonly-assigned U.S. Patent Number 6,423,583, which is hereby incorporated by reference herein in its entirety. The invention also contemplates that nanotubes 14 may be composed of a material other than carbon characterized by a band gap and semiconductor properties.

The term "horizontal" as used herein is defined as a plane parallel to the conventional plane or surface of insulating substrate 12 and the underlying wafer, regardless of orientation. The term "vertical" refers to a direction perpendicular to the horizontal, as just defined. Terms, such as "on", "above", "below", "side" (as in "sidewall"), "higher", "lower", "over", and "under", are defined with respect to the horizontal plane.

With reference to FIG. 2, a thin dielectric layer 20 is conformally deposited on the catalyst pad 10 and the insulating substrate 12. Dielectric layer 20 may be constituted by silicon dioxide (SiO_2) deposited by a low pressure chemical vapor deposition (LPCVD) process using tetraethylorthosilicate (TEOS) as the silicon precursor source. The dielectric layer 20 also coats an exterior of each of the carbon nanotubes 14 along their respective height or length. Many other materials may be used instead of TEOS-based oxide, as long as electrical isolation is ensured. The coatings on the carbon nanotubes 14 will define respective gate dielectrics 22 that participate as a feature in the structure of a field effect transistor (FET) device structure, as described below.

A blanket layer 24 of a conducting material deposited on the insulating substrate 12 fills the vacant spaces between adjacent carbon nanotubes 14 and covers the nanotubes 14, insulating substrate 12, and catalyst pad 10. Blanket layer 24 is electrically isolated from the insulating substrate 12 by portions of dielectric layer 20.

5 Suitable conducting materials for blanket layer 24 include, but are not limited to, doped polycrystalline silicon (polysilicon) and metals such as aluminum (Al), copper (Cu), gold (Au), molybdenum (Mo), tantalum (Ta), titanium (Ti), and tungsten (W). Blanket layer 24 may be deposited by any suitable deposition process such as CVD by thermal decomposition/thermolysis of a metal-containing precursor such as metal

10 halides and metal carbonyls, PVD, or sputtering. The thickness of the blanket layer 24 should completely cover the free ends of the insulator-covered carbon nanotubes 14. Each gate dielectric 22 electrically isolates the corresponding carbon nanotube 14 from the blanket layer 24.

With reference to FIG. 3, an exposed surface 26 of the blanket layer 24 is

15 polished flat by a chemical-mechanical polishing (CMP) process or any other suitable planarization technique. Generally, CMP processes involve a polishing or mechanical abrasion action aided chemically by a slurry introduced between a polishing pad and blanket layer 24. The thickness of blanket layer 24 is reduced by removing material to a depth such that the leading tips 16 of a significant number of carbon nanotubes 14

20 are substantially coplanar with the exposed surface 26 and accessible for subsequent processing.

With reference to FIG. 4, the exposed surface 26 of blanket layer 24 is removed selectively to the carbon nanotubes 14 so that the leading tips 16 project above the exposed surface 26. Techniques for recessing exposed surface 26 include

25 reactive ion etching (RIE) and wet etching with a suitable etchant solution. For example, polysilicon or aluminum constituting blanket layer 24 may be etched by RIE using a chlorine-containing gas, a bromine-containing gas, or a mixture thereof, which is known to be selective to SiO₂. The residual thickness of blanket layer 24 determines the channel length of the FET device structure.

30 With reference to FIG. 5, a recess 28 is formed in the blanket layer 24 that extends vertically from exposed surface 26 to the depth of dielectric layer 20. The

recess 28 is formed by a standard lithographic and etch process that patterns blanket layer 24 to expose unmasked areas in which recess 28 and other similar recesses for other like device structures will be formed and masked areas, and then etched by, for example, a dry etch process using, for example, NH_3 to remove the conductive material in the unmasked areas. Dielectric layer 20 serves as an etch stop layer. The blanket layer 24 is also partitioned or sectioned by a standard lithographic and etch process, which may be the same lithographic and etch process forming recess 28, into individual gate electrodes 30 that define the future location of individual FET device structures 42 (Fig. 8). Any carbon nanotubes 14 that may be present in the unmasked areas of blanket layer 24 are removed by the etch process forming recess 28 or may be eliminated by any other suitable process capable of removing the carbon nanotubes 14 from recess 28. The invention contemplates that the order of the process steps described with regard to Figs. 4 and 5 may be reversed so that the individual gate electrodes 30 are formed before the exposed surface 26 is recessed to expose the leading tips 16 of carbon nanotubes 14.

With reference to FIG. 6, an insulating layer 32 of a dielectric material is conformally provided that fills recess 28 and covers exposed areas of blanket layer 24 to cover the leading tips 16 of carbon nanotubes 14. The insulating layer 32 may constitute, for example, silicon nitride (Si_3N_4) deposited using LPCVD or plasma-enhanced CVD using NH_3 and silane (SiH_4) as precursor sources or SiO_2 , which may be deposited by a CVD process using TEOS as a precursor source. The portion of insulating layer 32 filling recess 28 electrically isolates the adjacent gate electrodes 30 from each other.

With reference to FIG. 7, the leading tip 16 of each carbon nanotube 14 is exposed above a planar recessed exposed surface 33 of insulating layer 32 and a length of the associated gate dielectric 22 is removed therefrom. To that end, insulating layer 32 is polished flat by a CMP process or any other suitable planarization technique to define the exposed surface 33. The exposed surface 33 is then further recessed relative to the carbon nanotubes 14 using one or more RIE processes that remove insulating layer 32 and gate dielectric 22 to the depth of the recessed exposed surface 33 selective to the carbon nanotubes 14. Alternatively, a

wet etch process using a suitable etchant solution, such as a buffered hydrofluoric acid (HF) solution, may be used. The carbon nanotubes 14 may have a distribution of lengths and although not shown, certain carbon nanotubes 14 may remain buried in the insulating layer 32 and/or the gate electrodes 30 after the exposed surface 33 is recessed.

5 With reference to FIG. 8, gate contacts 36 and source contacts 38 are formed by defining contact openings in insulating layer 32 at appropriate locations with a standard lithographic and etch process and filling the contact openings with a conductive material. The lithographic and etch process also defines areas of
10 conductive material that operate as drain contacts 40. Each gate contact 36 is electrically coupled, preferably ohmically, with one of the gate electrodes 30 and each source contact 38 is electrically coupled, preferably ohmically, with one of the catalytic pads 10. Each drain contact 40 is electrically coupled, preferably ohmically, with the leading tips 16 of carbon nanotubes 14 extending through the associated one
15 of the gate electrodes 30. Contacts 36, 38 and 40 are electrically isolated from each other and are formed from any suitable conducting materials including, but not limited to, Au, Al, Cu, Mo, Ta, Ti, and W deposited by, for example, CVD, PVD or sputtering. Standard back-end-of-the-line (BEOL) processing is used to fabricate and couple an interconnect structure linking contacts 36, 38 and 40 with corresponding
20 contacts of adjacent FET's.

 The completed device structure 42 forms an FET having a gate or gate region defined by one of the gate electrodes 30, a source or source region defined by catalyst pad 10 and source contact 38, a drain or drain region defined by drain contact 40, a semiconducting channel region defined collectively along the length of the carbon
25 nanotubes 14 extending through the associated gate electrode 30 with a vertical orientation relative to the horizontal plane of the insulating substrate 12, and a gate dielectric defined by each of the individual gate dielectrics 22 covering the nanotubes 14. Although only two completed device structures 42 are visible in Fig. 8, it is understood that multiple replicas of structure 42 are provided on insulating substrate
30 12 as detailed herein. Each completed device structure 42 is electrically coupled for device operation with additional circuit components (not shown) supported on

adjacent regions of the insulating substrate 12. Carriers flow selectively from the catalyst pad 10 through the carbon nanotubes 14 to the drain contact 40 when an electrical voltage is either applied via the corresponding gate contact 36 to one of the gate electrodes 30 to create a channel in the carbon nanotubes 14 extending
5 therethrough. The invention contemplates that, in certain embodiments, the catalyst pad 10 and source contact 38 may serve as a drain region and drain contact 40 may act as a source region.

With reference to FIGS. 9 and 10 in which like reference numerals refer to like features in FIGS. 1 and 2 and in accordance with an alternative embodiment of the invention, a capacitor device structure 50 (FIG. 10) may be formed by a different set
10 of processing steps performed subsequent to the device fabrication stage illustrated in Fig. 2. Specifically, the blanket layer 24 of a conducting material is planarized to a depth that is above the dielectric-covered leading tips 16 of the carbon nanotubes 14 and a layer 52 of conducting material is applied to the planarized blanket layer 24. A
15 contact (not shown) is electrically coupled with the catalyst pad 10 so that the catalyst pad 10 and the carbon nanotubes 14 supply one electrode or plate of the capacitor device structure 50 and the layer 52 supplies the opposite electrode or plate of the capacitor device structure 50. Dielectric layer 20 electrically isolates the two plates. The presence of the carbon nanotubes 14, which are covered by the dielectric layer 20,
20 increases the effective surface area of one of the plates.

As the carbon nanotubes 14 are semiconducting, a superimposed constant bias voltage must be applied to the plates of the capacitor device structure 50 so that the carbon nanotubes 14 conduct current. In an alternative embodiment of the invention, the carbon nanotubes 14 may be grown under growth conditions suitable to provide
25 the conducting molecular structure so that the constant bias voltage is not required.

While the present invention has been illustrated by a description of various embodiments and while these embodiments have been described in considerable detail, it is not the intention of the applicants to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will
30 readily appear to those skilled in the art. Thus, the invention in its broader aspects is therefore not limited to the specific details, representative apparatus and method, and

illustrative example shown and described. Accordingly, departures may be made from such details without departing from the spirit or scope of applicants' general inventive concept.